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Report No. DOE/JPL 955149 - 78/1
Distribution Category UC-63

(NASA-CR-162528) RESIDENTIAL PHOTOVOLTAIC
MODULE AND ARRAY REQUIREMENTS STUDY Final
Report (Burt, Hill, Kosar, Rittleman, and)
64 p HC A04/NF A01 CSCL 10B

N80-14482

G3/44 Unclass
46387

RESIDENTIAL PHOTOVOLTAIC
MODULE AND ARRAY REQUIREMENTS STUDY

JPL CONTRACT NO. 955149

LOW-COST SOLAR ARRAY PROJECT
ENGINEERING AREA

FINAL REPORT

June 1979

The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

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ACKNOWLEDGEMENTS

Paul Sutton of the Jet Propulsion Laboratory was the Technical Monitor for this study and Ronald G. Ross, Jr., is the Task Manager of the Engineering Area of the Low-Cost Solar Array (LSA) Project for which this study was performed. Their guidance and technical input to this study was deeply appreciated. Russell Sugimura of the Jet Propulsion Laboratory helped review the final report; his help and comments were appreciated.

The authors would also like to thank their family members for support and forbearance during the long weeks of work that were involved in the production of this document.

ABSTRACT

Burt Hill Kosar Rittelmann Associates has conducted a study to identify design requirements for photovoltaic modules and arrays used in residential applications.

Building codes and referenced standards were reviewed for their applicability to residential photovoltaic array installations. Four installation types were identified — integral (replaces roofing), direct (mounted on top of roofing), stand-off (mounted away from roofing), and rack (for flat or low slope roofs, or ground mounted). Installation costs were developed for these mounting types as a function of panel/module size. Cost drivers were identified. Studies were performed to identify optimum module shapes and sizes and operating voltage cost drivers. The general conclusion is that there are no perceived major obstacles to the use of photovoltaic modules in residential arrays. However, there is no applicable building code category for residential photovoltaic modules and arrays and early additional work is needed with standards writing organizations to develop residential module and array requirements.

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APPENDICES

1. Codes, Standards and Manuals of Accepted Practice-Definition and Importance

Codes, Standards and Methods of Accepted Practice are defined and the relationship between these types of documents with respect to the photovoltaic manufacturers and the building industry are addressed.

2. Regional Code Variations-Impact

The regional building codes - BOCA, SBCC, and ICBO - and their overlapping areas of jurisdiction are described. The impact of code-to-code variations is addressed.

3. Model and City Codes-Review

Model and city codes (ICBO, BOCA, SBCC, Pittsburgh and Los Angeles) are reviewed for their possible effect on the design of photovoltaic modules.

4. National Electric Code (NEC)-Review

The NEC was reviewed to determine its influence on the design of photovoltaic modules.

5. Types of Standards-Definition and Importance

Various types of standards used throughout the building industry are defined and discussed.

6. Federal Standards-Review

The HUD Minimum Property Standards (MPS) and the HUD-MPS supplement for solar heating and cooling were reviewed to determine the potential areas of influence on photovoltaic module design.

7. Standards Review Method

A method is developed to assess existing standards applicability to the design development of residential photovoltaic modules.

**8. Manuals of Accepted Practice (MAP)-
Purpose**

Discussions of the purpose of manuals of accepted practice and an outline of the development and contents of a perspective manual for the photovoltaic industry are provided.

9. Codes and Referenced Standards-Summary

A list of applicable codes, standards and addresses for obtaining such is provided.

10. Public Safety Testing Laboratories

The importance of public safety testing laboratories is discussed. Underwriters Laboratories services and procedures are discussed.

11. Insurance Review

A discussion of conversations with members of the insurance industry on the potential problems photovoltaic arrays may impose on the insurability of a residence is presented.

12. Studies Approach

A description of the method and assumptions used for the studies in the Appendices is presented.

13. Mounting Configurations

Details and assumptions developed for the four mounting configurations (rack, stand-off, direct and integral) are provided.

14. Module/Panel Size and Shape Cost Analysis

A discussion of size and shape requirements and their effect on cost is presented.

15. Grounding, Wiring, Terminal and Voltage Studies

Studies are provided on grounding, wiring, terminals and voltage to establish requirements for each as required by the NEC. Costing is provided showing the influence of voltage and wiring type.

16. Array Installation Cost Summary

A summary of all installation and materials cost is presented. Cost drivers are identified.

17. Photovoltaic Shingle/Module Comparison

A description of shingle and panel concepts and a comparison of these concepts is presented.

18. Retrofit Application

A discussion of problems and possible solutions to retrofit applications of PV arrays is presented.

19. Residential Photovoltaic Module and Array Performance Criteria

A performance criteria document is presented as a rough draft of a potential industry document.

**20. Critique of JPL's Solar Cell Module
Design and Test Specifications for
Residential Applications**

A review of the present JPL specification with commentary describing areas of potential problems, and improvements needed for an industry specification are summarized.

21. CSI Format Specification

A general specification format typically used in the building industry is presented along with an example.

Section 1

SUMMARY

This report presents the results of a study conducted by Burt Hill Kosar Rittelmann Associates. The objective of the study was to determine design requirements for residential photovoltaic modules and arrays. The approach used in accomplishing these objectives was to review existing building codes and their referenced standards for their applicability to residential photovoltaic module and array installations; to conduct studies of important attributes of the residence to the array, and attributes of the modules and arrays to their installation; and to design and cost a number of array mounting installation types to determine cost drivers.

The U. S. housing industry is large and complex but dominated by builders constructing fewer than 25 units per year. Because of this, it is an industry which relies on laws--building codes--to establish a minimum level of construction to protect the consumer, the home buyer. Supporting building codes (laws) are standards, which are voluntary and help interpret and measure the law, and manuals of accepted practice, which advocate appropriate installations and constructions. Interpretation of the laws (codes) is left with the local building code official, who may reject a product if, in his estimation, it does not meet code. To become a reality, residential photovoltaic power systems will have to comply with this existing framework.

To that end, existing building codes and their referenced standards were reviewed to determine what, if any, applicable requirements may be imposed on photovoltaic modules and arrays. Although this review produced design implications for modules and arrays, one major result of the review is that there is no current building code category for photovoltaic power systems, in general. Consequently, local building code officials can arbitrarily categorize modules and arrays so that undue restrictions or outright rejection can occur. To prevent this, requirements for residential photovoltaic power systems should be developed by the consensus process and, since this is a new evolving technology, these requirements

should be couched in the language of performance statements ("criteria") that are flexible enough to permit rather than inhibit new technology. A start on this document is presented in Appendix 19. For the long-term, however, work should begin with the Model Code groups to form working committees to begin developing draft code requirements using the performance criteria as its basis.

Since it takes about four years to modify the National Electrical Code (NEC), the NEC committee should be contacted immediately to form a photovoltaic subcommittee. Since photovoltaic systems are electrical in nature, compliance to the requirements of the NEC will be required. For the near term, performance criteria should be used. For the long term, classification of the photovoltaic system as a "Premanufactured Item with Internal Wiring" would offer the most latitude for product development while still preserving the necessary safety requirements.

Product approval of modules is necessary for their eventual acceptance by local building code officials. Early work is needed with approved nationally recognized testing laboratories to familiarize them with photovoltaic modules. (Underwriters Laboratories, Inc., is currently under contract to the JPL/LSA Project to investigate safety requirements for modules and arrays.)

Although there are uncertainties associated with not having an applicable code category, these are believed resolvable; the general conclusion of the codes and standards review is that there are no perceived obstacles to the eventual use of photovoltaic modules and arrays in residential power systems.

Following the codes and standards review, studies of important residence and array attributes were conducted, and design and costing of possible array mounting configurations were performed. Module costs were not considered. However, all peripheral costs associated with the support, installation, and wiring of modules to form arrays were studied. The array area was fixed at 1000 ft^2 to permit normalization of the results. The studies, as was the codes and standards review, were confined to the module and array and not the entire photovoltaic system.

From these studies, it was determined that an integrally mounted array, wherein modules are a structural roof member, composed of 32 by 96 inch panel/modules electrically connected using a modular quick-connect termination system was optimum from a cost and aesthetics standpoint. The installed cost of this array configuration is \$28.30/m² (1975\$) or \$39.70/m² (1980\$). The direct mounting configuration, wherein modules are attached to the roof over the waterproof membrane, had the next lowest installed cost of \$30.60/m² (1975\$) or \$42.90/m² (1980\$), and was aesthetically acceptable. Standoff and rack mounting were most expensive and had questionable aesthetics.

Aesthetic considerations play a prominent part in the shaping of new products for the housing industry. Photovoltaic array manufacturers should be very concerned over the visual effect of the array. Studies performed in this contract indicate that the module and array should approximate the mattelike (non-glare) texture of the roof; be rectangular (aspect ratio of approximately 2 to 1); and be a dark earth tone similar to surrounding roof material. The array should lie in and be a continuation of the roof plane and its texture. The array should not create a dominant, easily identifiable pattern. Also, the array should be as small as possible to avoid being a dominant monolithic feature, preferably 800 ft² (74 m²) or less. From the aesthetic standpoint, integral and direct mounted arrays are preferred.

Integral and direct mounted arrays would be considered roofing material by building code inspectors. This is an advantage because roofing materials are required to be qualified to UL 790, "Tests for Fire Resistance of Roof Covering Materials," Class A, B, or C, which qualifies the roofing as an entity. Although further investigation is needed to determine which fire class is appropriate, the requirements imposed on standoff and rack mounted arrays are more severe.

Standoff and rack mounted arrays would be considered as "roof panels," which impose requirements on roof-mounted plastics. Specifically, the plastic encapsulants must be code-approved, qualified separately (not in an encapsulation system) by a nationally recognized testing laboratory

to be in conformance to the code-specified test, ASTM D 635, "Flammability of Rigid Plastics Over 0.05 Inches in Thickness." Then, once the plastic materials are separately qualified, the total roof area of the encapsulated materials (now in modules) is further limited by the codes from 20 percent of the floor area (standard roof covering fire resistance) to 30 percent of the floor area (highest degree of fire resistance). For example, a 2000 ft² residence would be limited to between 400 and 600 ft² to approved plastic materials (modules) mounted on the roof.

Of the modules, themselves, a 32 by 96 inch panel/module, weighing 50 to 60 pounds, is optimum for ease of installation and cost. Array installations using modules smaller than 32 by 96 inches are far more expensive because of increased wiring costs to connect the modules into a panel, increased panel structural costs to support the module, and increased gasket or sealant to provide waterproofing.

Array wiring costs increase greatly as module size is reduced but do not vary significantly among the four array mounting configurations. Wiring costs are inversely proportional to branch circuit voltage level, the optimum (minimum) being between 100 Vdc and 300 Vdc. Electrical terminations are the principal cost drivers for array branch circuit wiring, although a modular quick connect wiring system can be significantly less expensive than junction box wiring systems particularly when the branch circuit wiring is exposed to weather. However, until such time as a modular quick-connect system is developed and code-approved, the J-box system should be used. Copper wire, No. 14 AWG, should be used. In dry locations, non-metallic sheathed (Type NM) or armored (Type BX) cable should be used. In wet locations, underground feeder and branch circuit (Type UF) cable should be used. Although wire sizes smaller in diameter than No. 14 AWG could be used, the greater volume production of No. 14 AWG gives it significant economic advantage.

In general, grounding is required, particularly when metal module support frames are used. Module and array designs that can demonstrate effective electrical isolation, as verified by a nationally recognized testing

laboratory, may be granted an exemption. For modules and arrays, a 50 psf design load will be acceptable for over 90 percent of the U.S. In areas with snow loads greater than 40 psf — portions of the Northeast, the Rocky Mountains, and Northwest — a higher design load or different installation may be necessary.

Finally, modules and arrays should be designed to be maintenance-free and have a design life of 20 years or more, which is consistent with roofing materials. To minimize a dominant aesthetic effect, array sizes should be as small as possible, preferably 800 ft² (74 m²) or less. This implies that module efficiencies should be as high as possible-- 13.5 percent or greater.

Section 2

INTRODUCTION

This final report documents a study of design requirements for photovoltaic modules and arrays used in residential applications. The study was performed by Burt Hill Kosar Rittelmann Associates for the Engineering Area of the Jet Propulsion Laboratory's Low-Cost Solar Array Project under contract number 955149 as a part of the U.S. Department of Energy's Solar Photovoltaic Conversion Program.

The primary emphasis of the study was on the design requirements imposed on the photovoltaic module, panel, and array by the residence. These impositions are the direct result of the way homes are built today and as they will be built in 1986, and are embodied in the documents which direct the design and construction of residences, namely, building codes and their referenced standards, and manuals of accepted practice. The study was conducted from the viewpoint of an architect, architect/engineer, or developer engaged to design homes using residential photovoltaic power systems.

The direct objectives of this study were:

- Identify electrical and mechanical design requirements for photovoltaic modules and arrays used in the residential sector.
- Determine installation cost sensitivities and their effect on module and array design.
- Evaluate module sizes and shapes to determine the optimum.
- Evaluate array operating voltage to determine the optimum.

The approach used in accomplishing these objectives was to review existing building codes and their referenced standards for their applicability to residential photovoltaic module and array installations; to conduct studies of important attributes of the residence to the array, and attributes of the modules and arrays to their installation; and to design and cost a number of array mounting installation types to determine cost drivers. The results of that effort are presented in this report.

2.1 TERMINOLOGY

Terminology used in the final report are illustrated in Figure 1. These come from the preliminary set of photovoltaic terminology and definitions established in 1978 by members of the Photovoltaics Program. The term "Residential Photovoltaic Power System" was not in the original definitions, but is provided for completeness.

2.2 REPORT FORMAT

This report is divided into the final report and its appendices. The final report is a distillation of the entire study and its implications on photovoltaic module and array design for the residential sector. Each summary topic in the final report references one or more appendices. It is in the appendices that the many facets of the overall study are revealed. Each appendix is a working paper on a residential topic, or the documentation of a study important to module and array design.

The appendices are included with the final report as an aid to anyone who desires to delve more deeply into the individual topics. Each appendix begins with its purpose, its conclusions, and any recommendations.

2.3 COST BASES

Costs presented in the final report and appendices are expressed in 1975 constant dollars unless stated otherwise. Costs were developed in first quarter 1978 dollars and converted to constant 1975 dollars by use of the JPL-supplied price deflator, 1.201. To convert to constant 1980 dollars, the value in 1975 dollars should be multiplied by 1.401.

2.4 UNITS

Despite attempts to change it, the residential construction industry remains rooted in the English system of units. It is not anticipated that the conversion of the industry to SI units will be easy or painless.

SOLAR CELL--THE BASIC PHOTOVOLTAIC DEVICE WHICH GENERATES ELECTRICITY WHEN EXPOSED TO SUNLIGHT

MODULE--THE SMALLEST COMPLETE, ENVIRONMENTALLY PROTECTED ASSEMBLY OF SOLAR CELLS AND OTHER COMPONENTS (INCLUDING ELECTRICAL TERMINATIONS) DESIGNED TO GENERATE DC POWER WHEN UNDER UNCONCENTRATED TERRESTRIAL SUNLIGHT

PANEL--A COLLECTION OF ONE OR MORE MODULES FASTENED TOGETHER, FACTORY PREASSEMBLED AND WIRED, FORMING A FIELD INSTALLABLE UNIT

ARRAY--A MECHANICALLY INTEGRATED ASSEMBLY OF MODULES TOGETHER WITH SUPPORT STRUCTURE AND OTHER COMPONENTS, AS REQUIRED, TO FORM A FIELD INSTALLED DC POWER PRODUCING UNIT

BRANCH CIRCUIT--A NUMBER OF MODULES OR PARALLELED MODULES CONNECTED IN SERIES TO PROVIDE DC POWER AT THE SYSTEM VOLTAGE LEVEL

RESIDENTIAL PHOTOVOLTAIC POWER SYSTEM--THE AGGREGATE OF ALL BRANCH CIRCUITS (ARRAY(S)) TOGETHER WITH AUXILIARY SYSTEMS (POWER CONDITIONING, WIRING, PROTECTION, CONTROL, UTILITY INTERFACE) AND FACILITIES REQUIRED TO CONVERT TERRESTRIAL SUNLIGHT INTO ELECTRICAL ENERGY SUITABLE FOR CONNECTION TO A RESIDENCE'S ELECTRICAL DISTRIBUTION SYSTEM OR A UTILITY ELECTRIC POWER GRID

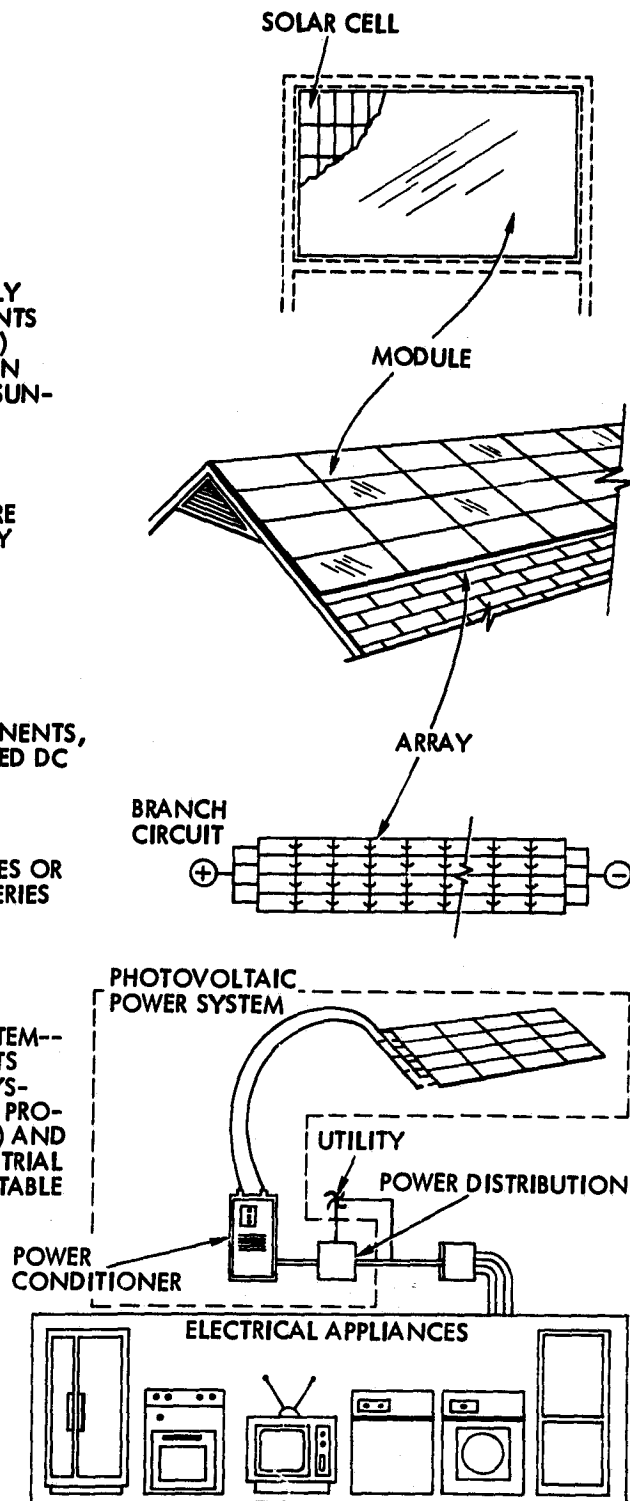


Figure 1. Residential Photovoltaic System Terminology

In fact, almost all building codes and their referenced standards use English units. Rather than indiscriminantly convert all measurements to SI units, it was decided to leave the English units as best representative of the industry today.

Section 3

CHARACTERISTICS OF THE RESIDENTIAL HOUSING INDUSTRY

To develop module and array requirements for residential photovoltaic applications, it is necessary to first understand the characteristics of the residential housing industry. These characteristics are the basis for implicit design requirements for products in that sector and must be considered, particularly if residential photovoltaic systems are to become commonplace.

3.1 HOUSING INDUSTRY OVERVIEW

The U.S. housing industry, probably the most complex of all industries, involves over 6 million people and accounts for five percent of the Gross National Product (GNP). To support the home buyer there are nine categories of activity: land acquisition and preparation, financing, contract construction, building trade unions, trade and professional groups, architects and engineers, material manufacturers and suppliers, marketing and sales, and government (code) officials. Most often these groups act independently with no strong overall management direction. Only the major developers attempt to join some of these groups.

The industry is highly fragmented. Builders constructing less than 100 units per year account for ninety percent of the housing market. The largest builder constructs less than one percent of new units annually. With the cyclical nature of the housing industry, and its complex structure, survival in the industry is the result of sharpening of business skills. Few large corporations could survive such market fluctuations. The entrepreneurial nature of many businesses throughout the industry keeps competition keen.

Products designed for this industry have to be simple to install. Due to its cyclical nature, unstable employment exists for almost 50 percent of the construction work force, resulting in a fluctuating skill level at the construction site.

Although innovation occurs in the housing industry, the industry as a whole is technically conservative. Builders are reluctant to consider innovation in a shrinking market while in an expanding market there is no incentive to change since housing demand exceeds supply.

It is the small builder, constructing fewer than 25 units per year, that is more likely to consider innovation, either with a new technique or product, since he is usually risking only one unit. Here, however, the small builder relies heavily on sub-contractors, dealers, and material suppliers for problem solving; he is very sensitive to warranties. Since he is seldom highly capitalized, cash flow and individual project accountability are a constant concern. First penetration of totally new products typically begins through small builders who build expensive, custom homes. Consumer demand then brings the new products into the mainstream of the industry.

The large builder, constructing more than 200 units per year, tends to be more innovative with new processes or techniques rather than new products since his construction is more speculative. He will occasionally innovate when he has the support of a major partner, such as a nationally recognized building material manufacturer, although innovation is sometimes done for image building. Since volume construction attracts more attention (building officials, union officials, demonstrators, etc.) than one-of-a-kind construction, the large builder is more sensitive to these groups and more image conscious. Innovation, when it does occur, is more likely to encompass the entire development rather than just a few houses since the cost to alter plans for a few houses is major. With larger developments, there is greater architect/engineer involvement since the fees can be spread over many repeat units. The large builder usually does not have the same ability for flexible decision making that the small builder has because the larger-scale financing involves added controls.

3.2 CODES, STANDARDS, AND MANUALS OF ACCEPTED PRACTICE

The function of building codes is to integrate this diverse industry to guarantee a minimum level of construction quality. Supporting building codes are standards and manuals of accepted practice.

Unfortunately, there is considerable overlap in the application of these three types of documents. In principal, a code should set forth a criteria, frequently making reference to a standard. The standard allows for many solutions to a particular design problem, all of which meet the predictable quality level specified by the standard. To permit ease of application of the most frequently used methods of meeting the standard, manuals of accepted practice were developed and have grown in importance. The building code official, whose responsibility it is to issue permits and approvals of the proposed building solutions, should make reference to all three types of documents with discernment. Details of these documents follow.

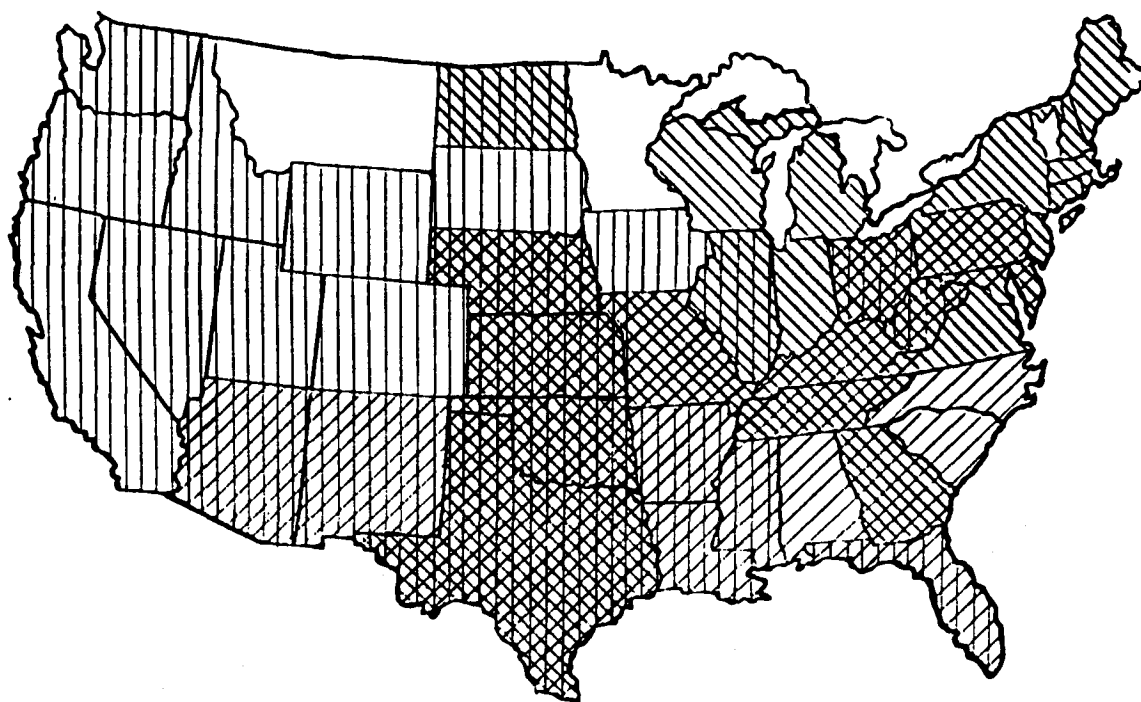
Building Codes. Building codes are laws whose purpose is to protect the health, safety, and welfare of the public. Being law, code changes are made by legislative process which is frequently complex and time consuming. Codes are the most permanent of the regulatory documents in the building industry.

Codes have two characteristics: they have been developed in response to a major (typically catastrophic) event calling attention to a need, and they have been adopted to organize and regulate an existing industry.

Because of this development, codes, prior to 1950, varied drastically from town to town as well as across the country. This lack of consistency caused concern to manufacturers, architects, engineers and builders whose business required crossing many code jurisdictional boundaries. To remedy this situation, Model Codes were developed. Although there are more than 40,000 local code jurisdictions in the United States with code enforcing authority, most of them adopt one or more Model Codes, sometimes with modification. Approximately 75 percent of all building

codes in force today are one of the Model Codes. The geographic areas of influence of the three prominent Model Codes are shown in Figure 2.

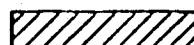
Safety of persons and property due to hazards arising from the use of electricity is the responsibility of the National Electrical Code (NEC). The National Electric Code has been recognized by all major Model Codes, building codes and most municipal codes. The only known exceptions to national acceptance are several municipal electrical codes such as those established by the City of Los Angeles and the City of Chicago.



● BUILDING OFFICIALS AND CODE ADMINISTRATORS (BOCA)
BASIC BUILDING CODE



● SOUTHERN BUILDING CODE CONGRESS (SBCC)
STANDARD BUILDING CODE



● INTERNATIONAL CONFERENCE OF BUILDING OFFICIALS (ICBO)
UNIFORM BUILDING CODE



Figure 2. Aggregate Code Map

Ideally, codes should provide a series of criteria which can be met with a variety of solutions. Codes written in this manner are generally referred to as performance language codes, rather than prescriptive language codes. The primary difference is flexibility. Performance language allows for a variety of solutions all of which meet criteria designed to protect public health, safety and welfare. Prescriptive language is quite specific, defining one method deemed acceptable and leaving little room for interpretation. Because of those distinctions, prescriptive codes are easy to monitor and enforce whereas performance codes are difficult to enforce due to their lack of specifics.

Building codes are, of necessity, complex documents. They must be general enough to address most questions which arise in the design and construction of a building, and yet comprehensive enough to provide the public protection that is intended. Many situations arise, however, where interpretation of or variance with the code is necessary. In most jurisdictions, there is a three level procedure for handling interpretations and variance. Details of this procedure can be found in Appendix 1.

Standards. In contrast with codes, standards are not laws. The purpose of standards is to offer ways through which code criteria can be met. Standards concern methods whose results meet a predictable quality level. A standard is a model, which defines a measure by which code criteria can be evaluated. Standards, developed by the consensus process, are promulgated by the professional community that is involved with the application of the technology. Standards respond to state-of-the-art and change as technologies develop and are tested through application. They are subject to change more quickly than codes and can exist in an evolving state if professional communities pursue their development.

Standards are used extensively in codes. They permit the code to state by what method or procedure compliance is obtained. This is normally done by reference, although occasionally, a standard will be embodied in the code. Like codes, standards can be written in either performance or prescriptive language.

Four generic types of standards exist — Specification, Test Method Standard, Classification Standard, and Recommended Practice. Definitions of these and other details concerning standards can be found in Appendix 5.

Manuals of Accepted Practice. Supporting both codes and standards are manuals of accepted practice, which describe proven procedures or techniques which are most often used within the housing industry to provide a formula through which the characteristics required in a standard can be achieved. A manual is prescriptive by nature but it is not a law. Produced by the housing industry or trade associations, a manual describes procedures typical for that industry and may carry the marketing or design prejudices of that group. Manuals of accepted practice change quickly as they evolve with technology, developing procedures through which a technology can be applied. They are widespread throughout the housing industry, and can be regional in nature, addressing locally applicable methods and materials. Additional information can be found in Appendix 8.

3.3 PRODUCT APPROVAL

Product approval, wherein the manufacturers show compliance of their product to the building codes, is the "teeth" of the building code process. Since building codes are laws, a product cannot be legally used unless it is approved.

Some products need only an interpretation (usually based on a cursory inspection and minimal testing of a product's characteristics) to be accepted in a code jurisdiction. Most often, however, new products are approved only after extensive testing and certification of compliance with various standards. Unlike the Western European nations, there is no single product approval procedure or agency in the United States. The Model Code groups have established product approval procedures in an attempt to simplify the process, but it remains cumbersome and expensive for a manufacturer to gain product approval in every jurisdiction in the country. Figure 3 illustrates the time required for product acceptance to occur in cumulative jurisdictions. Although this figure may at

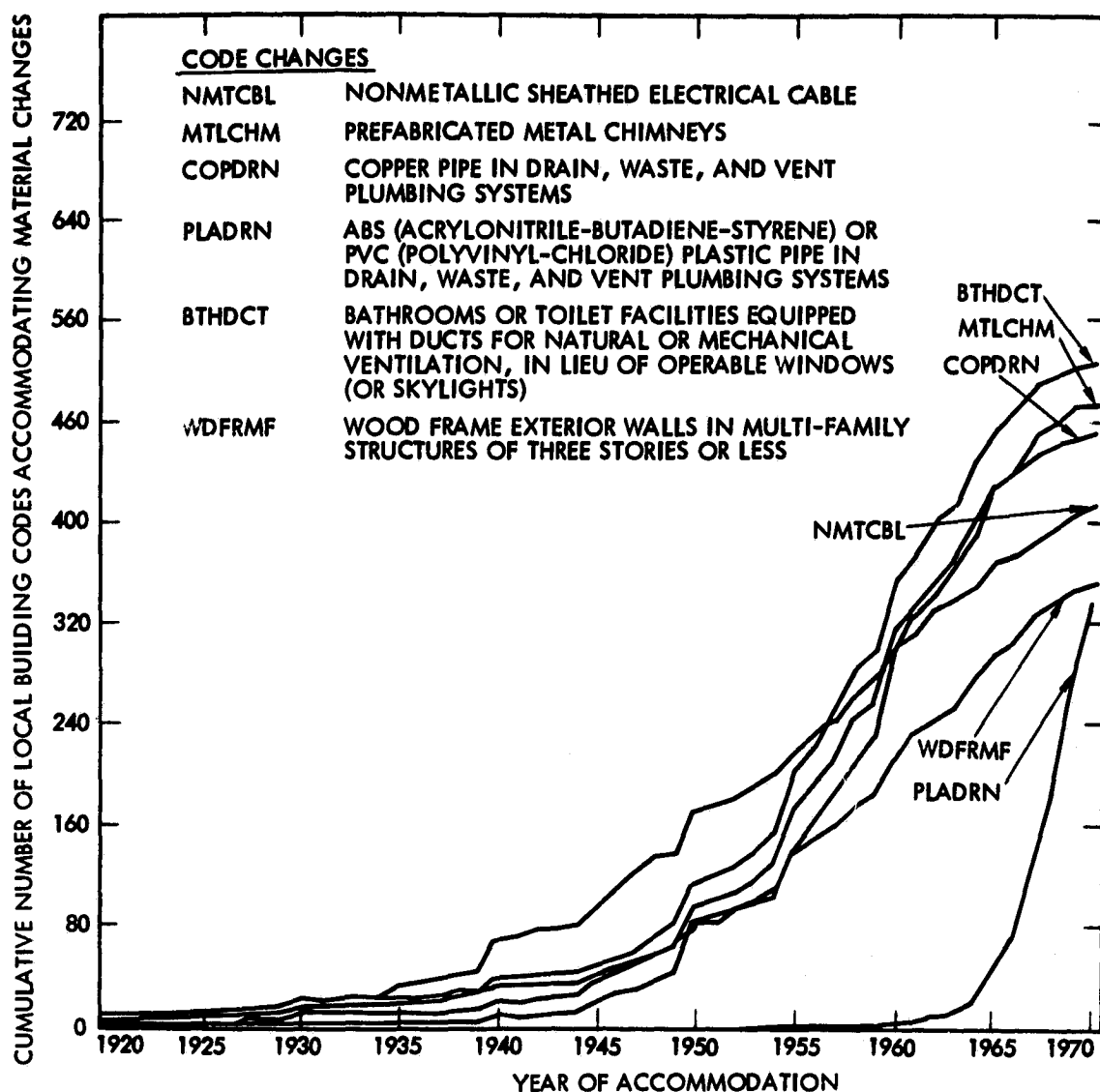


Figure 3. Cumulative Number of Local Building Codes Accommodating Material Changes, By Year

first appear to discourage manufacturers of photovoltaic products, it should be noted that all of the examples shown are replacement innovations, intended to displace an existing product or process. This conflict with tradition and vested interests causes more resistance to code approval than new innovations having no existing competition. This should be encouraging to the photovoltaic industry that while product acceptance for a new concept is a lengthy and expensive procedure, it will not be encumbered by the traditional resistances most replacement

innovations experience. A more extensive discussion on gaining product acceptance in the United States can be found in the paper, "Decision-Aiding Communications in the Regulatory Agency: The Partisan Uses of Technical Information," by F.T. Ventre, in Appendix 1.

Manufacturers who market nationally tend to follow a general pattern for product approval. First, the building codes are searched for the most stringent regulations. Then an approved national testing laboratory reviews the standards referenced by that code and conducts product testing to show conformance with the existing applicable standards (also known as "listing"). Then the product is submitted for review and approval by code officials; any supplemental testing required by their review is performed so that the product receives their approval. Finally, the product is submitted for Model Code approvals. This is usually the last extensive effort taken by the manufacturer directly. Once the product is approved by the most stringent codes for his product and/or by one of the Model Codes, these approvals and their associated test results are used by the manufacturer's representatives, dealers, or local building contractors to secure product approvals in additional code jurisdictions. It may be necessary for the manufacturer to lend assistance, but the bulk of the effort is leveraged through local representatives.

Occasionally conformance with the more stringent code is economically unsound, if it represents a small market area and the remaining codes can be met with a less expensive product.

3.4 SUMMARY

Although the aggregated housing industry is large and complex, the principal actors are the small builders, those constructing fewer than 25 units per year. Because of this, it is an industry which relies on laws, in the form of building codes, to establish a minimum level of construction quality to insure the safety of the occupants. To support the building codes (laws) are consensus standards, which are not laws but voluntary agreements among interested and concerned parties. These

help interpret and measure the law, and are easier and quicker to change as the state-of-the-art changes since they are not bound by the legislative process. Standards are frequently referenced by codes. Supporting codes and standards are manuals of accepted practice, which help interpret the intent of the standards by advocating appropriate installations and constructions.

To ensure that building codes are complied with, product approval is required. Local code officials have the authority by law to reject any product that in their opinion does not meet the requirements of the code. Manufacturers who supply this market go to great pains to ensure their product is acceptable; they spend considerable sums to have the product inspected, tested, and certified.

Manufacturers of new products for this market, such as photovoltaics, will do well to consider the dead weight of historic precedents when trying to penetrate this market. Products must be easy to handle and install, they must be fairly rugged to survive outside service, and they must meet code. Based on history, first penetration of totally new products typically occurs in the more expensive, custom homes, filtering down to the less expensive "Spec" (Speculative) homes through consumer demand.

Section 4

RESIDENTIAL MODULE/ARRAY DESIGN IMPLICATIONS

In conducting this study, a great deal of useful information was compiled. To maximize its use, it was decided to provide short topic summaries in this section and the complete details in appendices. Since each topic summary may not be sufficient for those who may desire to do in-depth investigation or analysis, the appropriate appendix containing detailed information is referenced.

It is premature to consider these design implications as requirements. This report is the first detailed investigation of residential modules and arrays. Further review of these design implications as well as additional similar investigations into the remainder of the residential photovoltaic system — power conditioning, storage (if applicable), and utility interface — are needed before design requirements for modules and arrays can be established.

4.1 CODES AND STANDARDS REVIEW IMPLICATIONS

Three model codes — BOCA, ICBO, and SBCC; two municipal codes — Los Angeles and Pittsburgh; and the National Electrical Code (NEC) were reviewed along with their referenced standards to determine what, if any, applicable requirements may be imposed on photovoltaic modules and arrays. Together, these codes and referenced standards cover the basic residential building requirements for over 96 percent of the United States (based on population). In general, this review has produced design implications for modules and arrays appropriate for the residential construction industry; however, existing local ordinances could modify them. (These reviews can be found in Appendices 2, 3, 4, and 6.) Table 1 summarizes the implications from this review.

One major result of the review is that there is no applicable current building code category for residential photovoltaic modules and arrays. Although this conclusion was anticipated, the impact of this is severe: local building code officials can arbitrarily categorize modules and

Table 1. Codes and Standards Review Implications
and Recommendations

Topic	Finding	Implication	Recommendation
<ul style="list-style-type: none"> ● Building code category (Model Codes, Municipal Codes, and National Electric Code) 	<ul style="list-style-type: none"> ● No applicable building code category currently identified 	<ul style="list-style-type: none"> ● Local building code officials could restrict or reject PV arrays 	<ul style="list-style-type: none"> ● Near-Term: Develop performance criteria by the consensus process. ● Long-Term: Form Model Code committees to draft code requirements.
<ul style="list-style-type: none"> ● National Electric Code (NEC) 	<ul style="list-style-type: none"> ● Key document; takes four years minimum from draft till publication 	<ul style="list-style-type: none"> ● Earliest impact of subcommittee work is 1984 edition 	<ul style="list-style-type: none"> ● Near-Term: Form subcommittees in 1979 to draft requirements for PV systems. Meanwhile, use performance criteria. ● Long-Term: Attempt to have classified as "Premanufactured Item with Internal Wiring."
<ul style="list-style-type: none"> ● Code approval 	<ul style="list-style-type: none"> ● Required 	<ul style="list-style-type: none"> ● Product testing/ approval may be required before local building code officials will accept PV modules and arrays 	<ul style="list-style-type: none"> ● Contact nationally recognized testing laboratories regarding standards and tests required for product approval.
<ul style="list-style-type: none"> ● Obstacles 	<ul style="list-style-type: none"> ● No perceived obstacles to limit eventual use of PV modules and arrays in residential power systems 		

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arrays with the result that undue restrictions or outright rejection can result. To prevent such a setback, the near-term implication is that requirements for residential modules and arrays (and the remainder of the system) should be developed by the consensus process and, since this is a new evolving technology, those requirements should be couched in the language of performance statements ("criteria") that are flexible enough to permit rather than inhibit new technology. A start on this document is provided in Appendix 19, "Residential Photovoltaic Module and Array Performance Criteria." However, for the long-term, work should begin with the Model Code groups to form working committees to begin developing draft code requirements using the performance criteria as its basis.

Since it takes about four years to modify the National Electrical Code (NEC), the NEC committee within the National Fire Protection Association (NFPA) should be contacted immediately. Since photovoltaic systems are electrical in nature, compliance to requirements in the NEC will be required. However, the NEC was written without consideration for photovoltaics and these requirements do not yet exist. Since a photovoltaic subcommittee could have its first impact in the 1984 version of the NEC, it is recommended that contact be made with the NEC this year to form a subcommittee to begin drafting the requirements for photovoltaics in the residential housing industry. The basis for the draft requirements would be the performance criteria, and, for near term residential applications, the performance criteria should be used. As questions arise regarding the intent of the NEC, code interpretations should be sought by manufacturers, architect/engineers, or users. For the long term, it is felt that photovoltaic systems would be best classified (i.e., that classification allowing manufacturers, architects, and installers the most latitude while preserving the necessary safety requirements) as a "Pre-manufactured Item with Internal Wiring." This is the category that, for example, heating/air conditioning systems fall under. Within the line item, say, Photovoltaic Power System, the system requirements can be identified and the subsystem/component requirements can be referenced to other sections of the NEC that apply. (Some of these other sections would have to be newly written.)

Connected with developing consensus standards, and eventually codes, is obtaining product approval. Normally the residential product approval process begins with a new product designed to replace an existing application. Applicable codes already exist; typically test standards to meet the intent of the code also exist. Such is not the case with residential photovoltaic modules and arrays. Early work is needed with approved national testing laboratories to familiarize them with the product and the application. Without product approval, local building code inspectors may reject their use. (Underwriters Laboratories, Inc., is currently under contract to the JPL/LSA Project to investigate safety requirements for photovoltaic modules and arrays.)

Despite not being able to find an appropriate building code category for residential modules and arrays, the general conclusion of the review is that there are no perceived obstacles to the eventual use of photovoltaic modules and arrays in residential power systems. Uncertainties associated with not having an applicable code category are believed resolvable and are discussed in the next section.

4.2 SUMMARY MODULE/ARRAY DESIGN IMPLICATIONS

The design implications contained in this section are distilled from the appendices into short topic summaries contained in the following tables. Discussion of the summary tables follows.

Overall Design Implications. Overall design implications are summarized in Table 2. Besides the cost implication, two other implications are prominent — lifetime and performance.

It is important to differentiate between the design life and the actual or historical life of a residence. As used in this report, design life is the intended service life, the specific number of years of service, that building materials, components, and assemblies are designed to survive and operate. The number of years that the building materials, components, and assemblies indeed survive is the historical life, which is based on actual data.

Table 2. Overall Design Implications

Topic		Module/Array	
● Lifetime	● Design life of 20 years and maintenance-free		[Appendix 19]
● Performance	● Array efficiency of 13.5% or greater at NOCT		[Appendix 19]
● Cost	● Minimum cost commensurate with maintenance-free, 20-year design life		[Appendix 14]

The lifetimes of residential building materials, components, and assemblies are not the same. The historical life of the structure is about 55 years; roofing lasts 15 to 25 years, depending on locale and the type of material used; plumbing lasts 10 to 20 years, depending on the condition of the water; and of the major appliances, stoves last 10 to 15 years and refrigerators last 10 years.

Without similar long term data for residential photovoltaic arrays, it is impossible to state its historical life. However, a design life can be inferred.

The historical life most analogous to residential photovoltaic arrays is roofing. Residential arrays will be mounted on top of roofing (stand-off and rack mount) or will replace roofing (direct and integral mount). Residential arrays will be exposed to the same environment as roofing and, in the case of the direct and integral mount, will have the same function as roofing — water shedding. So, it is appropriate that residential photovoltaic modules and arrays have the same life as roofing, namely, its design life should be 20 years, minimum.

One other consideration is that throughout its design life, periodic maintenance must be minimized. The module and array must be designed to be trouble-free. Continuing maintenance is not appropriate for a residence, and, particularly, for roofing. Rather than tolerate continuing annoyances, homeowners are likely to turn off the system. When compared with the most complicated apparatus in a residence, the heating/air conditioning system, the implications for troublefree design of a photovoltaic system, which neither heats nor cools its owners, becomes clear.

The other implication, performance, comes from aesthetic considerations. Basically the problem is one of engineering acumen versus aesthetic tastes, the latter usually dictating. Based on previous studies, 93 m^2 (1000 ft^2) of ten percent efficiency array — 10 kWp — appears optimum from a cost standpoint. However, aesthetically it is very difficult to achieve a pleasing residential architecture with such a dominant monolithic feature. Less array area is preferred. 74 m^2 (800 ft^2) can be

accommodated easier than 1000 ft². This, however, implies an array efficiency of 13.5 percent to achieve the same 10 kWp output. Although 56 m² (600 ft²) is preferred, this implies a 16.7 percent efficient array, which may not be achievable with the current level of technology.

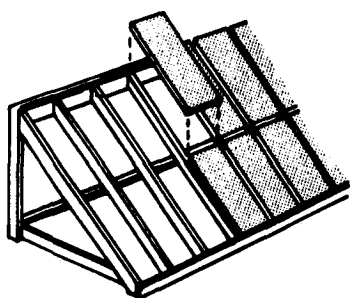
Mechanical Design Implications. Mechanical design implications are summarized in Table 3 and identify concerns with size, shape, and weight; dimensional tolerances; and mounting configuration.

The physical dimensions of modules and panels (the latter containing modules smaller than full-size) should allow for convenient handling by no more than two (and preferably one) installers, each having a grip span of 36 to 40 inches and capable of lifting 50 to 60 pounds. However, this study eliminated panels comprised of modules smaller than full-size based on installed cost. Of the two candidate module sizes identified — 32 by 96 inches (nominal) and 48 by 48 inches (nominal), weighing 50 to 60 pounds (one man carry) to 100 to 120 pounds (two man carry) — the 48 by 48 inch module was later eliminated by aesthetic considerations.

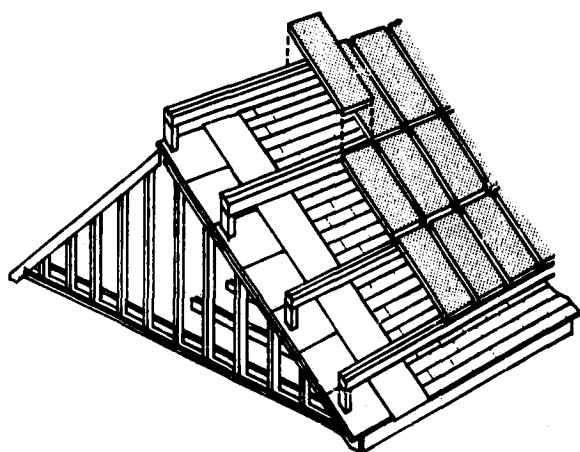
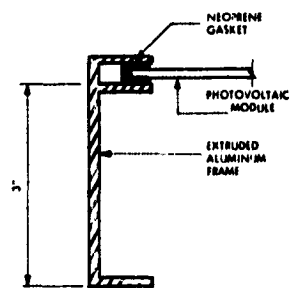
Dimensional tolerances currently used within the housing industry indicate dimensional tolerances for glass modules of +1/8, -1/16 inch for dimensions under 48 inches; and +3/16, -1/16 inch for dimensions over 48 inches. For other module construction types, tolerances would have to be calculated using guidelines found in Appendix 14. For an array, tolerances should be calculated based on the module construction type, mounting configuration, and dimensions.

The design of panel-type modules should be standardized for use in any of the four mounting configurations — rack, standoff, direct, and integral (see Figure 4). Shingle-type modules are suitable for direct mounting only.

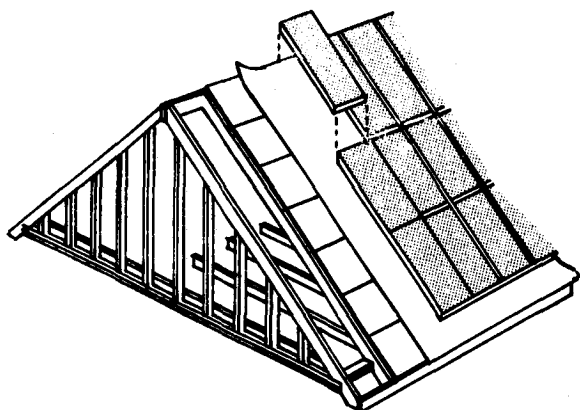
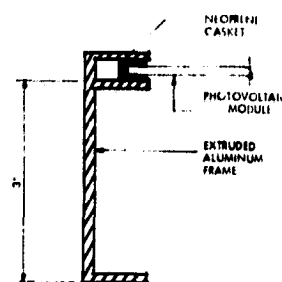
Results of the study did not identify an optimum configuration. However, in order of lowest to highest installed cost, the four configurations are integral, direct, standoff, and rack. Based on lowest installed cost, the preferred configuration is integral mounting of the module, wherein



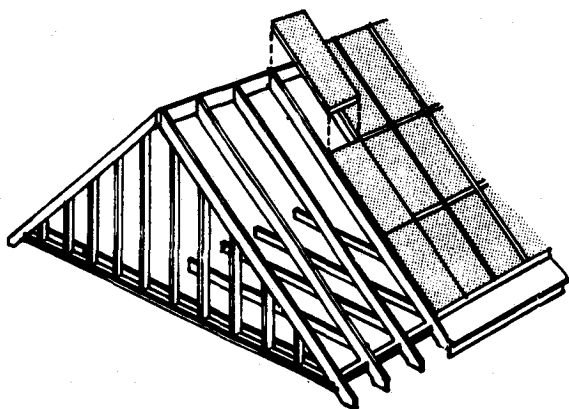
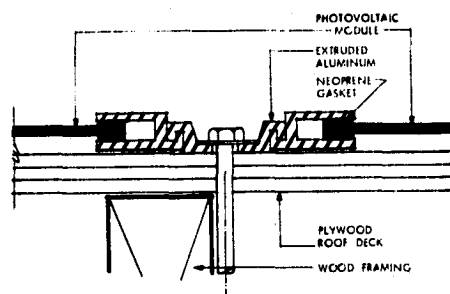
Rack



Standoff



Direct



Integral

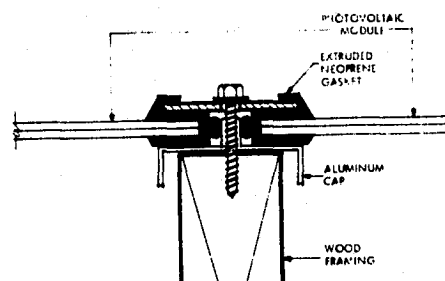


Figure 4.

Table 3. Mechanical Design Implications

Topic	Module	Array
• Size, shape, and weight	• 32 x 96 in. (nominal), weight: 50 to 120 lb.	—
	[Appendix 14]	
• Dimensional tolerances	<u>Glass Modules</u> • +1/8, -1/16 in. — Dimensions under 48 in. • +3/16, -1/16 in. — Dimensions over 48 in.	• Calculate for module construction, mounting configuration, and array dimensions
	[Appendix 14]	[Appendix 14]
• Mounting configuration	• Standardize panel-type modules for use in any of four configurations • Shingle-type modules direct-mounted only	• Integral-mounting of module; module/array is a structural roof member
	[Appendix 14]	[Appendix 16]

the array replaces roofing and substructure. However, it requires very tight tolerances on roof structure to provide the required watertightness. Additionally, the module must transfer all live loads to the roof structural members. Venting can aid back-surface cooling but construction interfaces (typically ventilation blockage due to improperly installed insulation) can cause temperature differentials across the array. This configuration is an aesthetically acceptable solution, but further development is necessary, and is recommended.

The next lowest cost configuration is direct mounting of the module to the roof over a water-tight membrane. Problems inherent with this configuration include cooling (only the top surface is exposed), installation and maintenance (electrical connections must be made from the top or side), and water shedding (water cannot be permitted to accumulate under the module).

Standoff mounting, wherein the module is supported away from the surface of the roof, eliminates problems associated with direct mounting, but with a penalty of increased cost. Since the installation is not required to form the watertight membrane, water passes easily under the module, as does air, which provides some back surface cooling. Module loads are transferred to the building structure using a minimum substructure, typically plywood.

Rack-mounting is the most costly, has the least aesthetic appeal, and has the most severe structural limitations (large point loadings) of all the configurations. The slant height is limited to 16 feet because of aesthetic and structural limitations. Its only applicability is with flat-top roofs and here, depending on the presence of a parapet, aesthetic considerations may limit its use.

The design of shingle-type modules should follow many of the implications listed in Table 3. Based on a review of current R&D shingle modules and the development of generic shingle module concepts (see Appendix 17), future shingle module designs should strive to be rectangular, lightweight, pliant, and sized for easy handling and fast installation with a minimum number of interconnections. They should be durable

to resist weathering and tough to withstand shipping and rough handling at the job site. Since shingle-type modules are a form of direct mounting, it is recommended that their development be pursued.

Retrofit of existing buildings to incorporate arrays was investigated. Positioning of the array for optimum tilt angle and off-south azimuth is a potential problem. Those buildings with good south exposure and non-tile roofs can accommodate the additional structural load imposed by the array with no problem - in general buildings are designed for roof-loads of up to 18 psf. In some cases additional array area can be accommodated by add-on structures such as a garage.

Electrical Design Implications. Electrical design implications are summarized in Table 4. In addition to voltage level, two other implications are prominent: terminations and wiring; and grounding.

Results of wiring studies indicated that #14 AWG copper wire should be used for interconnection of modules. Wire size was determined by optimizing the material cost and the ampacity (the ability to carry current). Although wire sizes less than #14 AWG could satisfy the current requirements, the larger production of #14 AWG copper wire and its consequent reduced cost result in it being the preferred choice.

The type of cable (assembly of insulated conductor) is dependent on the array mounting configuration. The #14 AWG copper wire should be used in non-metallic sheathed cable (Type NM) or armored cable (Type BX), for dry locations, and in underground feeder and branch circuit cable (Type UF), for wet locations. Only existing types of cable were investigated because code-approved cables are more readily accepted by local code officials.

Externally (off module) mounted J-boxes should be used for electrical terminations until a modular quick disconnect system, which was preferred based on lowest installed cost, is developed and code-approved.

Table 4. Electrical Design Implications

Topic	Module	Array
• Voltage level	• 100 Vdc to 300 Vdc	
		[Appendix 15]
• Terminations and wiring	• Copper wire, #14 AWG	
	Dry locations: Non-metallic sheathed (Type NM) or armored (Type BX) cable	
	Wet locations: Underground feeder and branch circuit (Type UF) cable	
	• Use off-module J-box until quick-connect system is developed and code-approved	
		[Appendix 15]
• Grounding	• Ground the installation	
	• Exceptions may be granted where live parts are effec- tively isolated electrically	
	• Code-approval required	
		[Appendices 4 and 10]

The whole area of module interconnection and termination needs further development. The approach used in the study was to investigate existing code-approved or potentially code-approved electrical interconnection hardware so that near-term applications can be fielded easily with a minimum of local code problems. For the long-term, however, development of integral cabling assemblies that are low-cost, maintenance-free, and code-approved is mandatory.

With respect to grounding, the installation shall be grounded particularly if any metal frame or parts can become energized. Exceptions may be granted for modules and/or arrays where live parts are effectively isolated electrically from any conducting materials. Code approval will be required by local code officials to assure compliance. Some requirements of grounding may be clarified in the near future as the result of a current JPL/LSA Project contract with Underwriters Laboratories, Inc.

Safety Design Implications. Table 5 summarizes the safety design implications: general, installation and maintenance, fire, and electrical insulation and grounding.

The general implication from this study is that photovoltaic systems, including modules and arrays, will be required to comply with the electrical requirements of the NEC. Photovoltaic systems are electrical in nature and the responsibility of the National Electrical Code is the safety of persons and property due to hazards arising from the use of electricity. As discussed in Section 4.1, until photovoltaic systems are covered in the NEC, manufactureres, architects, and users should seek clarification from the NEC when questions arise.

Safety of modules and arrays must be considered throughout the entire design process, from manufacturing to installation and maintenance including abnormal but possible events like fire. Each phase in this process imposes safety requirements that must be addressed and solved by the design of the module and array.

Table 5. Safety Design Implications

Topic	Module	Array
<ul style="list-style-type: none"> General 	<ul style="list-style-type: none"> Compliance to NEC required. 	[Appendix 4]
<ul style="list-style-type: none"> Installation and maintenance 	<ul style="list-style-type: none"> No shock hazard when handled in sunlight Design for simple installation and maintenance-free operation 	[Appendices 4 and 15]
<ul style="list-style-type: none"> Fire 	<ul style="list-style-type: none"> Qualify per UL790. Class A, B, or C fire test (Integral and Direct) 	[Appendix 3]
<ul style="list-style-type: none"> Electrical insulation and grounding 	<ul style="list-style-type: none"> 1600 Vdc voltage withstand 	(Same as electrical design implications - grounding)
	[Appendix 15]	

One safety design implication coming from the installation and maintenance of modules and arrays is that of shock. There is a potential electrical shock hazard when handling, installing, and maintaining photovoltaic modules and arrays. Although the shock may not be lethal, a resulting fall from the roof could be. Although no regulations now exist, regulations governing the installation of the modules and arrays would likely come from the Occupational Safety and Health Agency (OSHA). Three potential solutions to this problem follow.

1. Provide a quick-connect electrical termination assembly with no exposed live parts on either the male or female fittings.
2. Provide a quick-connect electrical termination assembly that will internally short circuit the module when the fittings are parted.
3. Provide the module with an opaque cover such as strippable paper which would shield the surface during shipping, handling and installation. When the array was completely assembled and wired, the protective paper would be removed.

The module's electrical insulation system and grounding system must be designed as a whole. The array grounding philosophy places requirements (limitations) on the insulation system. For the near term, residential modules should be designed for a voltage withstand of 1600 Vdc. This is based on the Underwriters Laboratories guidelines for ac equipment of twice the working voltage plus 1000 volts, and a 300 Vdc maximum array operating voltage. This should provide adequate voltage isolation over the life of the system if the appropriate electrical stress values are known, which is currently not the case. Electrical stress parameters for module insulation (encapsulation) systems are currently being surveyed by Bechtel National, Inc., for the JPL/LSA Project. Further data from that study may lead to design improvements in the module electrical insulation (encapsulation) systems commensurate with the life, performance, and cost goals, and the array's grounding philosophy.

Another related implication is that installation and maintenance ease and safety should be designed into the module and array. For example, modules with glass top covers are hazardous to work on because of their

slick surface. In this case, special equipment and/or procedures must be developed to facilitate safe installation and maintenance.

Fire safety, addressed by all the codes reviewed, was emphasized by the National Fire Protection Association (NFPA) Code. Residential modules and arrays installed on the roof of one and two family dwellings will probably be required to conform to existing building code restrictions for roof coverings. These restrictions permit limit combustibility in contrast with high density residential construction, or commercial, industrial, and institutional construction where fire resistance and non-combustibility requirements are more severe. Problems have arisen, however, in the application of the existing fire code requirements to photovoltaic modules and arrays.

The most potentially severe fire code restriction uncovered in the study is the limitation placed on items categorized as roof-mounted plastics. Rack or standoff mounted residential photovoltaic modules and arrays can be considered by local code officials to be "roof panels," which impose the following restrictions:

1. The plastic encapsulants must be code-approved, qualified separately (not in an encapsulation system) by a nationally recognized testing service (Underwriters Laboratories, Inc., for example) to be in conformance with the code-specified test, ASTM D635, "Flammability of Rigid Plastics Over 0.05 Inches in Thickness."
2. Once the plastic materials are separately approved, the total roof area of the encapsulated materials (now in modules) is further limited by the codes from 20 percent of floor area (standard roof covering fire resistance) to 30 percent of floor area (highest degree of fire resistance). For example, a 2000 ft² residence would be limited to between 400 and 600 ft² of approved plastic material (modules) mounted on the roof.

On the other hand, direct and integral mounted residential photovoltaic modules and arrays would be considered as roof coverings by local building code officials. Here, modules and arrays qualified by a

nationally recognized testing service to be in conformance with UL 790, "Tests for Fire Resistance of Roof Covering Materials," could be installed on the roof of the residence without any area restrictions. It is recommended, however, that further studies be undertaken to determine the applicability of Class A, B, and C requirements to photovoltaic modules and arrays since the extent to which roof materials must be fire resistant is dependent upon geographic location and the degree of fire danger.

Aesthetic Design Implications. Table 6 summarizes the aesthetic design implications: size, texture, pattern, and color. The impact of residential construction aesthetics on the photovoltaic array is considerable. The majority of home buyers are extremely conservative and bound to tradition. Any new, strong design impact, which requires market conditioning and challenges tradition, should expect to encounter initial negative reactions. However, if the design of the modules and arrays are tempered with aesthetic considerations, the initial negative public reaction should be minimized.

The four basic elements of residential aesthetic design that should be addressed in the design of the photovoltaic module and its integration into the residence as an array are size (scale), texture, pattern, and color.

The array size, as discussed in the overall design implications, presents a problem to residential aesthetics. One thousand square feet of any material in a single plane is more dominant than any other existing material or surface design criteria in the present residential housing industry. The less array area, the better the aesthetics. This, of course, has overall efficiency implications of 13.5 percent at NOCT for the near term goal of 74 m^2 (800 ft^2) of array area. Also, the arrays should lie in the plane of the roof of the residence - implying direct or integral mounting - and be as continuous as possible. Discontinuous arrays create, in addition to aesthetic problems, many mechanical and electrical problems.

Table 6. Aesthetic Design Implications

Topic	Module	Array
<ul style="list-style-type: none"> • Size (scale) 	—	<ul style="list-style-type: none"> • 74 m² (800 ft²) preferred with efficiency of 13.5% or greater at NOCT (10 kWp) • Lie in and be a continuation of roof plane <p>[Appendices 13 and 17]</p>
<ul style="list-style-type: none"> • Texture 	<ul style="list-style-type: none"> • Approximate matte-like texture of the roof <p>[Appendix 17]</p>	<ul style="list-style-type: none"> • Array is continuation of the texture of roof plane. (Direct or integral mount) <p>[Appendix 17]</p>
<ul style="list-style-type: none"> • Pattern 	<ul style="list-style-type: none"> • Rectangular, approximately 2 to 1 <p>[Appendix 17]</p>	<ul style="list-style-type: none"> • Subdued with rectangular pattern elements (modules) <p>[Appendix 17]</p>
<ul style="list-style-type: none"> • Color 	<ul style="list-style-type: none"> • Dark earthtone, similar to surrounding roof material 	<p>[Appendix 17]</p>

The texture of the module and array should ideally be similar to the matte-like quality of the roofing material. The array should not be an additional roofing element but, rather, should be a continuation of the texture of the roof material and plane, the latter again implying a direct or integral mount. A matte-like finish on the module may, however, cause more dirt retention and consequently more performance degradation than a smooth glass finish, but the smooth glass finish is not aesthetically pleasing. Creative architectural designs or innovative glass engineering designs may help to minimize this problem, but until then a matte-like finish should be a design goal for residential modules and arrays.

The pattern of the array should be subdued and rectangular. Any installation with a scale (size) problem should not be accompanied by a strong pattern; the overall aesthetic effect would be negative. This means the pattern should be as subdued as possible, implying that the framing be the same color and texture as the module and surrounding roofing material. It should be difficult for an observer on the ground to identify the joint between module and framing.

Secondly, the elements of the pattern (modules) should be rectangular. This rectangular pattern is carried throughout the residential industry and the only square shapes used are usually less than one foot square, such as ceramic tile and vinyl floor tile. The module shape should consider the classic rules of proportion; typically, a two-to-one ratio.

The array color should be dark brown or a dark earthtone color similar to the surrounding roofing material. The framing should be the same color as the module.

Environmental Design Implications. Table 7 summarizes the environmental design implications. As a result of the study, many existing test standards were found in related areas of environmental design and are referenced or incorporated in Appendix 19. Discretion should be exercised in the use of these test standards until their applicability is determined by the JPL/LSA Project. Relevant ones are listed in Table 7.

Table 7. Environmental Design Implications

Topic	Module	Array
• Structural loading	• 50 psf design load	[Appendix 3]
	• Pass ASTM C393 flexure test	[Appendix 19]
• Moisture resistance	• Structural and other metal parts pass ASTM D2247	[Appendix 19]
• Fungus	• Pass MIL-STD-810C, Method 508.1, Procedure I	[Appendix 19]
• Shipping and handling	• Provide temporary stiffeners if flexural rigidity is required during handling	[Appendix 17]
	• Pass MIL-STD-810C, Method 516.2, Procedure I (Shipping Test) and Procedure II (Transit Drop Test)	[Appendix 19]
	• Shipping containers pass ASTM D775 drop test	[Appendix 19]

First and foremost of the environments is structural loading. Here the various loads - dead, live, wind, seismic, constraint (thermal), ice, hail, and maintenance - all act on the module and array during its service life. The module and array must be designed to survive these anticipated loads acting individually or collectively. By review of the various regional loads identified by the Model Codes and their referenced standards, it was determined that a module design load of 50 psf would be appropriate for over 90 percent of the continental United States, excluding only high wind and high snow areas. This design load was derived using static design load tables and techniques. Other design techniques, such as ultimate design, could have been used and, although resulting in a higher design load, could result in lighter and less expensive structures and/or modules. Use of those techniques should be investigated as part of integrated module/array design studies.

Once the design loading is known, the module (and the array) must be designed to withstand flexure due to distortion in its installed position. It is difficult to achieve even pressure along the perimeter of a flat panel. Although torque wrenches are provided on large industrial glazing projects to achieve even pressure, they are not appropriate for use in the housing industry and their use should be avoided. The flexure properties of modules can be tested using ASTM C 393, "Standard Methods of Flexure Test of Flat Sandwich Construction," which is used by the glazing industry.

Currently the JPL/LSA Project is providing guidelines and test procedures for evaluating encapsulation materials for a variety of environmental conditions. These test procedures are being evaluated continually to determine their applicability for the appropriate failure or degradation mechanism within the module. Because the procedures are developed specifically for modules, they should be used in the future as the basis for photovoltaic industry standards.

The following existing test standards, found during the study, which may be relevant are incorporated into Appendix 19:

- Humidity test for structural and other metal parts, ASTM D 2247, "Coated Metal Specimens at One Hundred Percent Relative Humidity."
- A rain test is needed, particularly for direct mounted panel-type modules, and shingle-type modules. MIL-STD-810C, Method 506.1 could serve as the basis of an industry standard.
- Fungus test, MIL-STD-810C, Method 503.1, Procedure I.
- For modules and arrays expected to be installed in a salt-laden (Wastal) environment, ASTM B 117, "Standard Method of Salt Spray (Fog) Testing," followed by an electrical test.

The design of photovoltaic modules for the residential industry must accommodate the construction habits and characteristics of that industry. It is not uncommon for building material components during shipping and handling to be subjected to stresses far in excess of what they will experience in actual service. For example, sheets of glass, which are sufficient to withstand design wind loads when installed, can be easily broken if they are carried flat by two men over a rough building site. Such considerations must be taken into account by the module manufacturer. Packaging methods and materials should preclude the need for handling procedures of any kind. For example, if a module design requires flexural rigidity during handling, temporary stiffeners should be provided by the module manufacturer.

Until specific photovoltaic standards are developed, two test methods which may be used with discretion to evaluate modules for shipping and handling stresses are MIL-STD-810C, Method 516.2, Procedure I (Shipping Test) and Procedure II (Transit Drop Test); and ASTM D 775, "Standard Method of Drop Test for Shipping Containers."

Shingle Module Design Implications. The shingle-type module integrates a photovoltaic module into a roofing element. The module is direct mounted on the roof using standard roofing techniques (ideally), each module needing only enough structural rigidity to survive shipping handling and installation. The resultant array blends in with other roofing materials (ideally), forming an aesthetically-pleasing

installation. Although the current R&D shingle module design establishes technical feasibility of this concept, it was found to be labor intensive design, involving over 3000 interconnections to form a 1000 ft², 10 kWp array (see Appendix 17).

Review of the preceding implications and current building materials and practices suggests that a 1986 shingle module should be larger in size with higher packing efficiency (rectangular solar cells) to minimize installation. This module should utilize materials consistent with current roofing and have a dark earthtone color. Figure 5 illustrates a possible design.

It is felt that further work is necessary to fully develop the potential of the shingle type module.

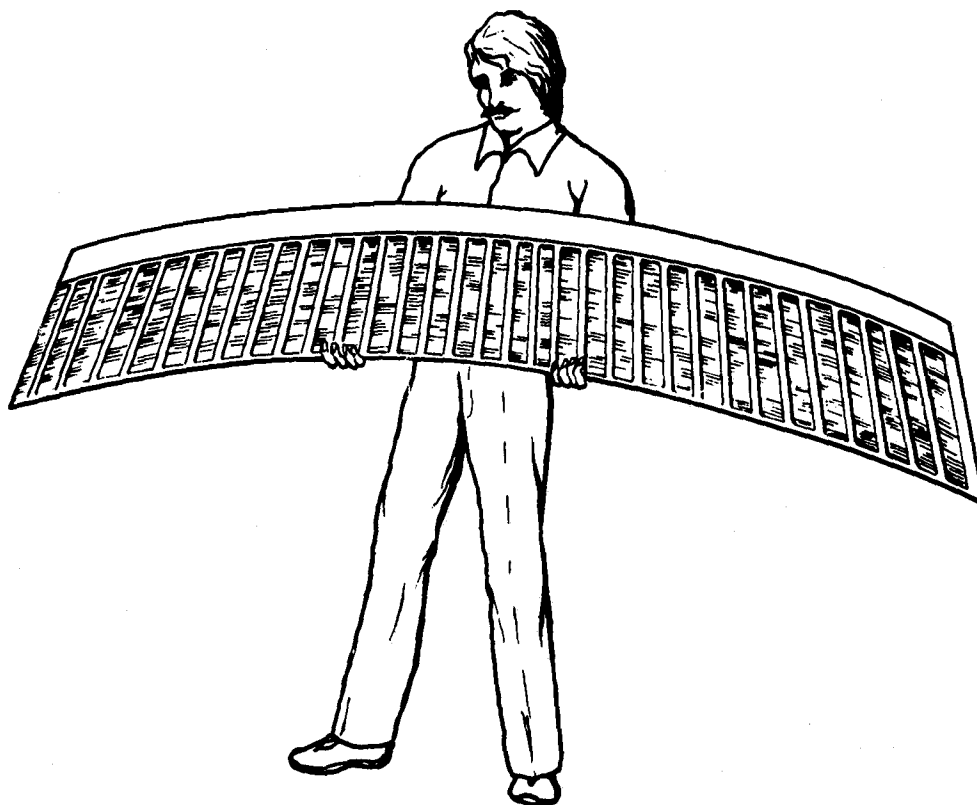


Figure 5. Potential 1986 Shingle Module Design

4.3 COST TRADE-OFF IMPLICATIONS

This section summarizes the residential photovoltaic array installation cost data developed during the study. The cost data assumes a mature market, one wherein all components are readily available and site labor is familiar with the installation practices. No quantity discounts were assumed, as could be expected in a housing development; rather, the costs are consistent with a builder who constructs 50 to 100 individual houses per year using the same technology and construction practices. The costs shown represent the builder's costs, including marketing and distribution for the site materials used - sealant, gaskets, wood, etc., and excludes indirect costs such as architect/engineering and sales fees. The total installed cost does not include the cost of the photovoltaic module, but is the additional cost for a builder to install the photovoltaic modules into a residential array.

The cost data were derived using array installation details which are consistent with current housing practices but are not optimized. This was done so that cost drivers, when identified, would indicate areas where current practice could be improved upon through technology development. The structural load used to develop the details was 50 psf. To maintain consistency, industry cost-estimating tables were used.

Cost data in this section were summarized from Appendices 14, 15, and 16.

Array Voltage. Table 8 summarizes the wiring cost data for the 32 by 96 inch panel/module. Three different voltage levels - 30, 100, and 220 Vdc - and two termination types - J-box and modular quick-connect - were evaluated for three different array sizes. The 8 by 133 ft array is an extreme case; most residential housing do not have 133 ft of continuous roof available. The other two array sizes - 16 by 67 ft and 24 by 45 ft - are more realistic.

As seen in the table, the wiring costs decrease as voltage level increase. This is illustrated in Figure 6 for the 16 by 67 ft array. The reason for the drop is primarily the savings in conductor sizing; as the voltage

Table 8. Wiring Costs for 32 by 96 Inch Panel/Modules

Condition/ Termination	WIRING COSTS, 1975 \$/m ²								
	8 x 133 (99.1 m ²) Array			16 x 67 (99.1 m ²) Array			24 x 45 (101.1 m ²) Array		
	30 Vdc	100 Vdc	220 Vdc	30 Vdc	100 Vdc	220 Vdc	30 Vdc	100 Vdc	220 Vdc
<u>DRY</u> Modular	11.90	6.70	6.10	10.40	6.30	5.90	9.60	6.10	6.00
J-Box	11.40	6.70	6.30	9.90	6.90	6.20	10.00	6.60	6.40
<u>WET</u> Modular	12.40	7.20	6.60	10.90	6.70	6.40	9.90	6.60	6.40
J-Box	17.40	13.20	12.80	16.40	13.40	12.70	16.70	13.10	12.90

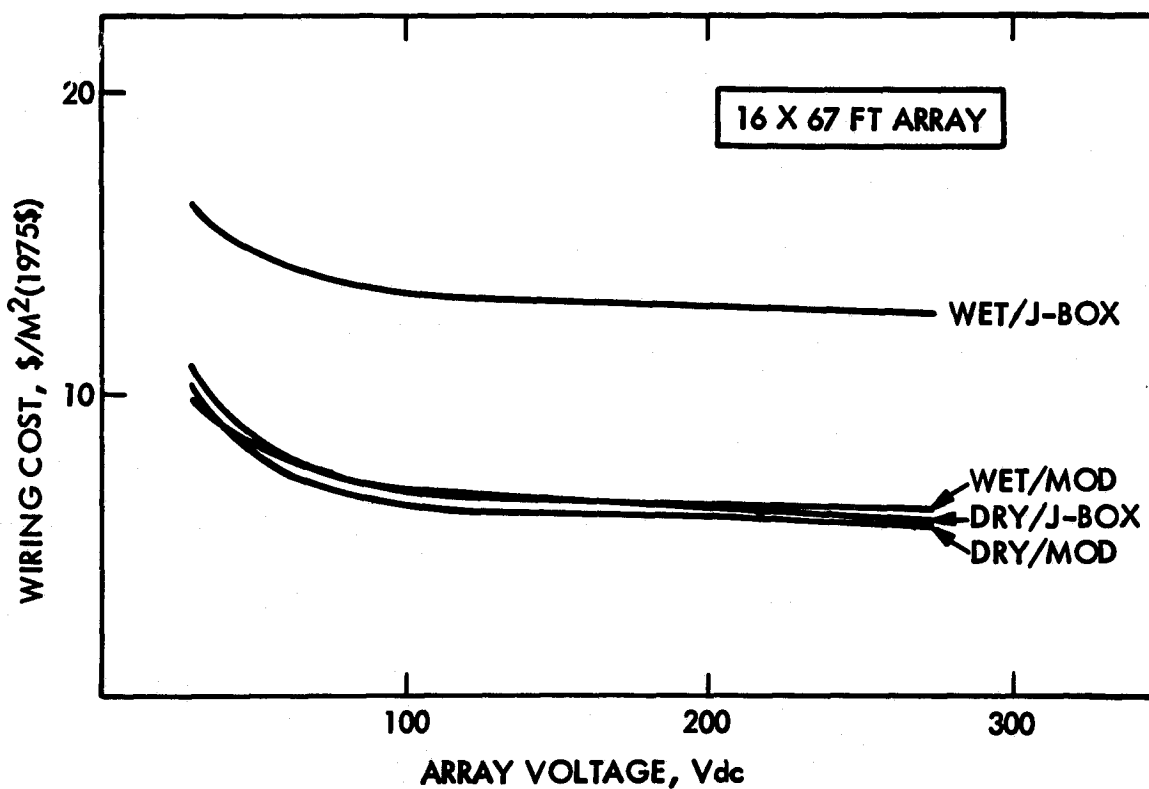


Figure 6. Wiring Costs Versus Array Voltage for 32 by 96 Inch Panel/Modules in 16 by 67 Foot Array

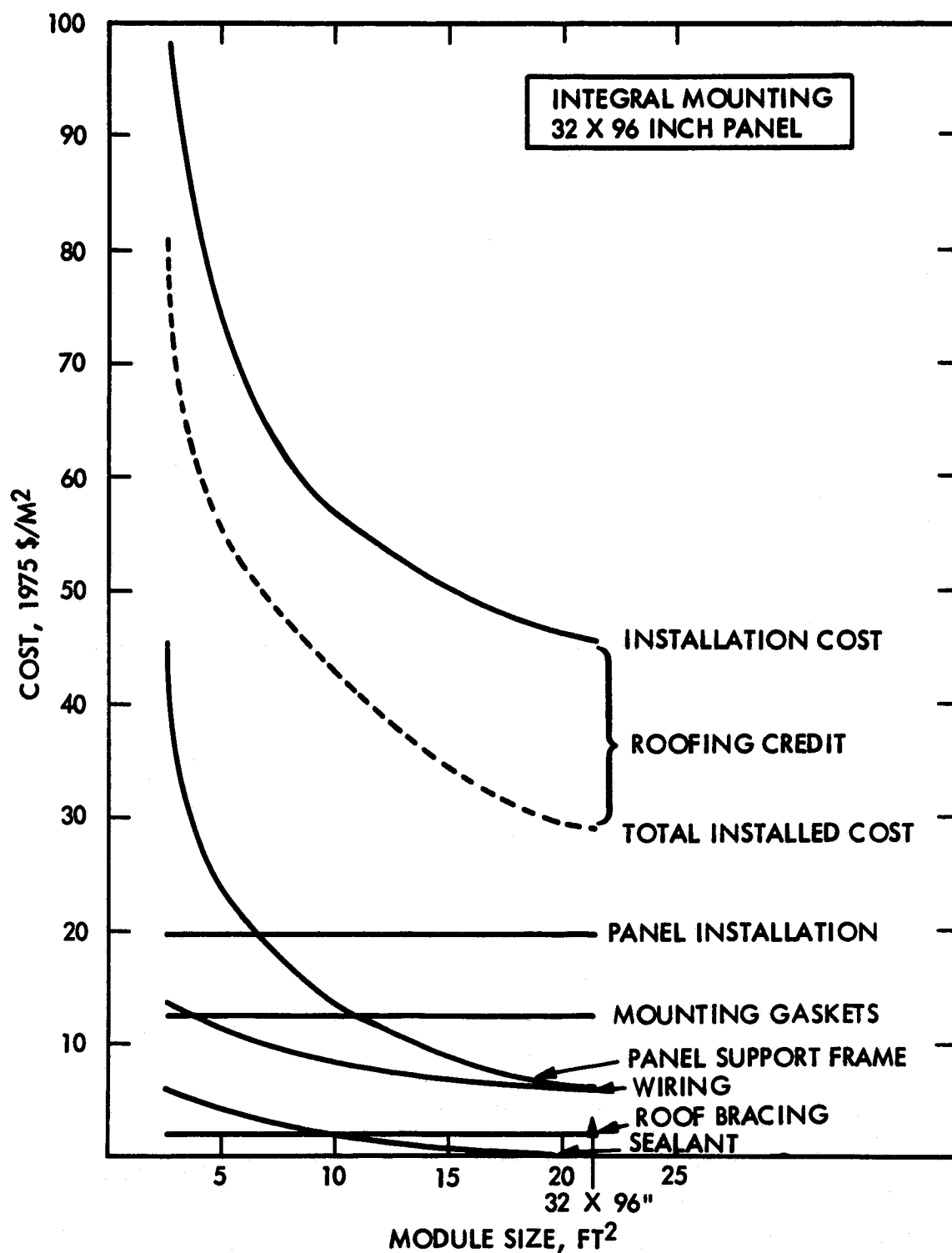


Figure 7. Integral Mounting -- Array Costs Versus Module Size

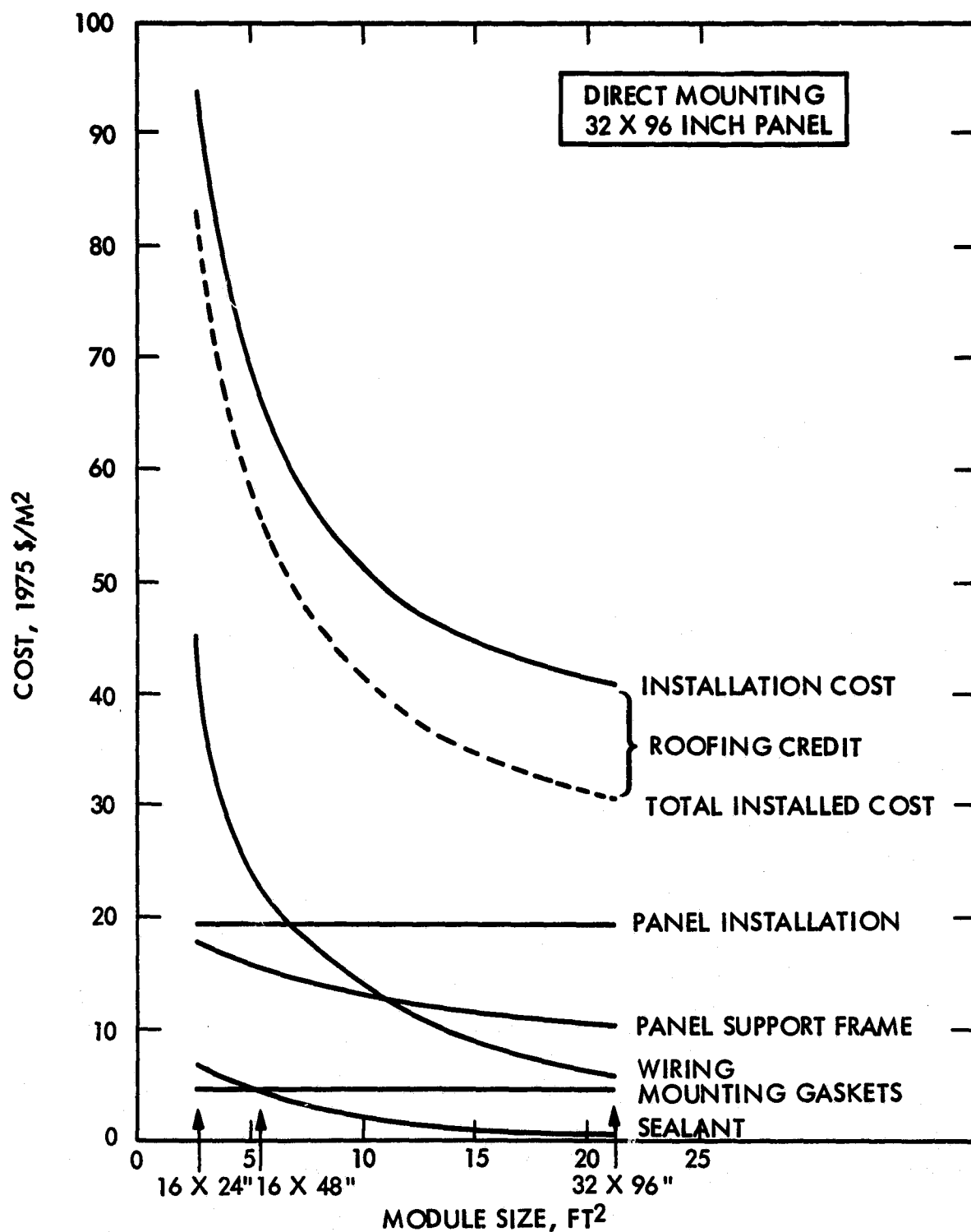


Figure 5. Direct Mounting -- Array Costs Versus Module Size

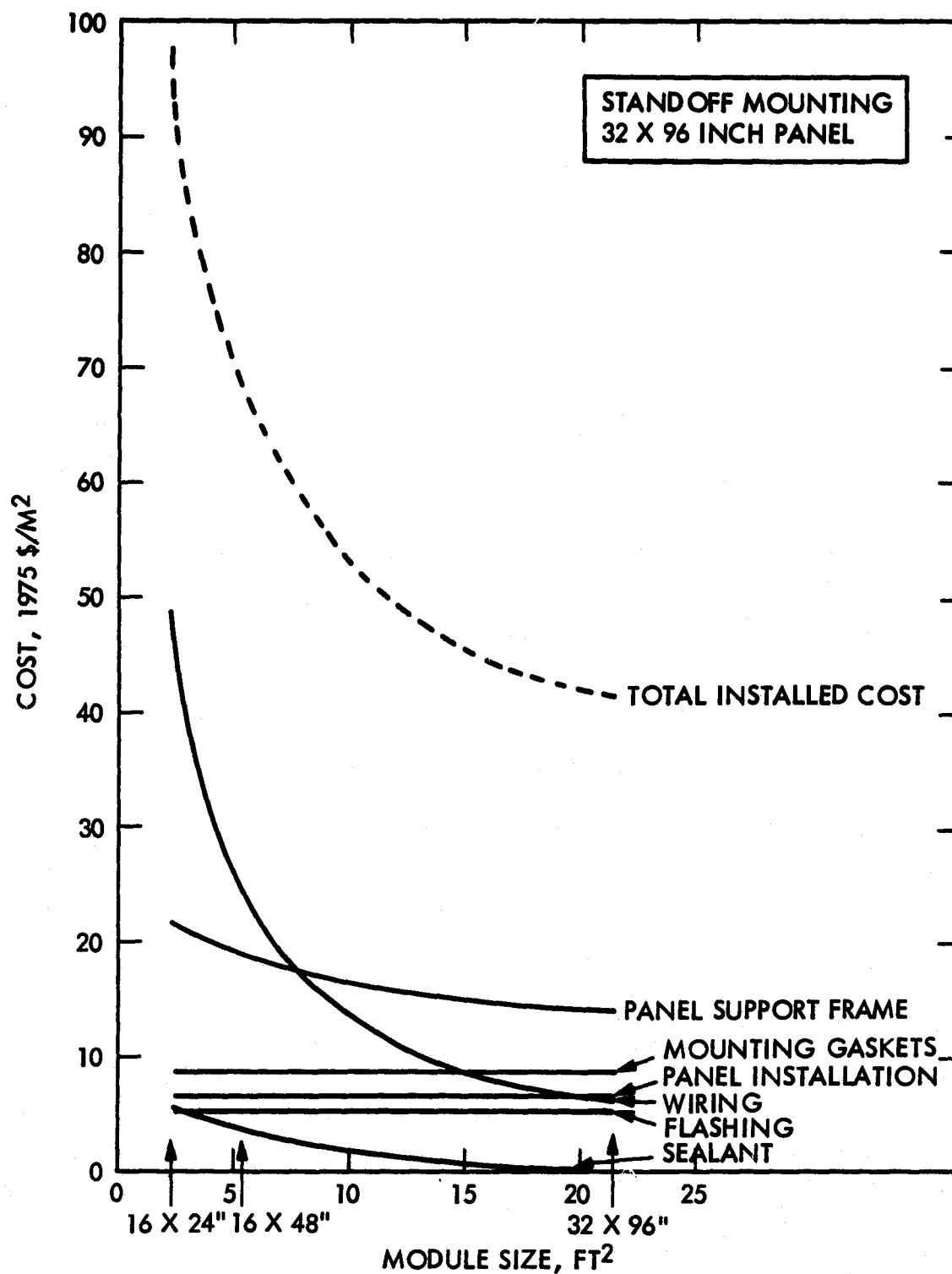


Figure 9. Standoff Mounting -- Array Costs Versus Module Size

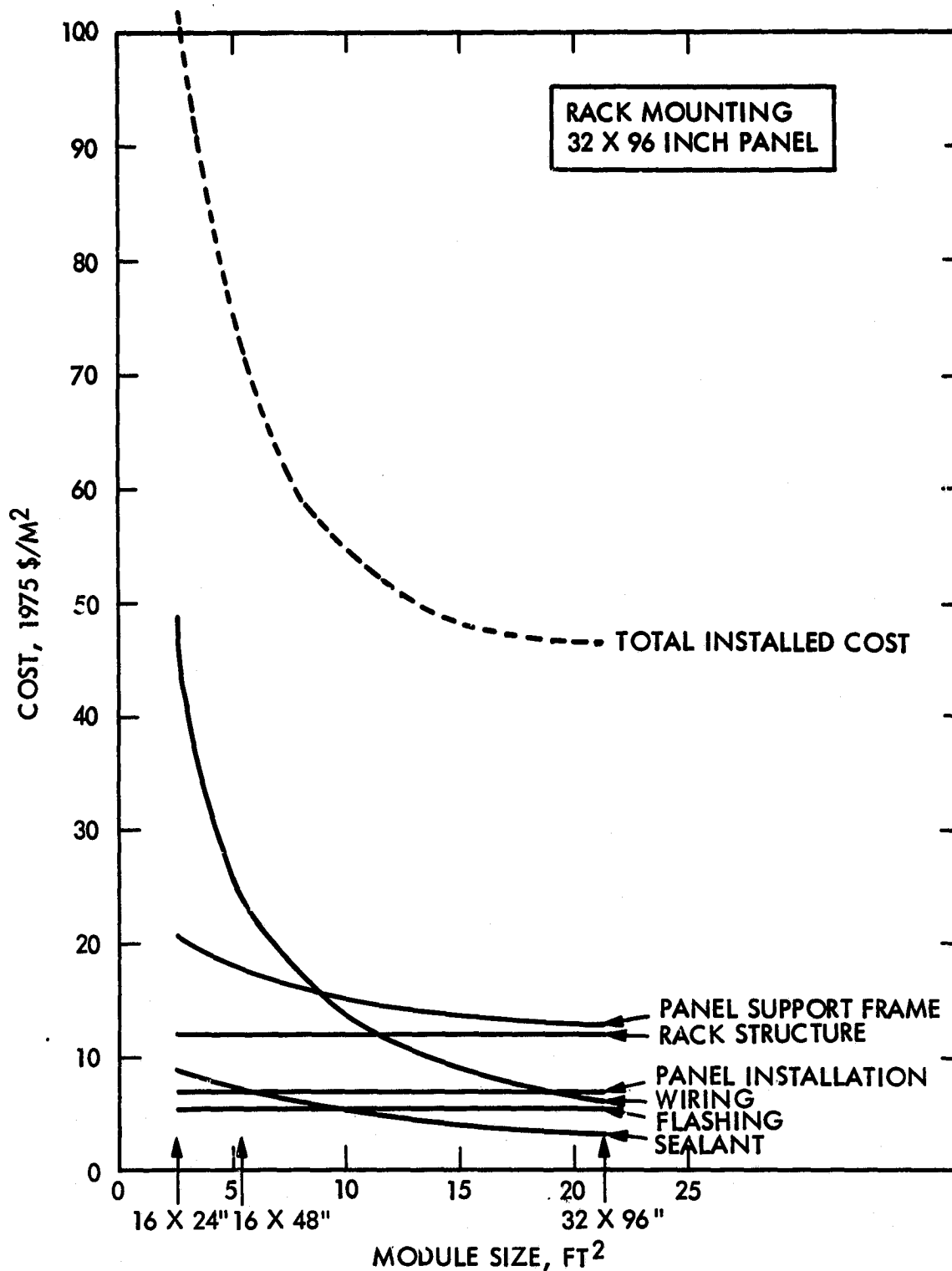


Figure 10. Rack (Roof) Mounting -- Array Costs Versus Module Size

increases, the current decreases, and the wire diameter decreases. As seen in Figure 6, the optimum array voltage ranges between 100 and 300 Vdc, and in that range, the modular quick-connect termination system costs less than the J-box system.

Module Size. Figures 7 through 10 illustrate the effect on installed cost of using modules other than full-size in the array. Three module sizes were evaluated, 32 by 96 inch (full-size), 16 by 48 inch, and 16 by 24 inch. As is seen in the figures, the installed cost increases as module size decreases. This is due to increased wiring costs to connect the modules into a panel, increased panel structural costs to support the modules, and increased sealant or gaskets to provide water-proofing. As is seen from the figures, the optimum module size occurs when the module is the same size as the panel - 32 by 96 inch.

A roofing credit was included for the integral and direct mounting configurations because normally used roofing materials are not needed in the area these array configurations will be installed on. The roof credit used, that displacing 325# asphalt shingles, is consistent with the 20 year design life assumed for the modules and array.

Array Mounting Configuration. Table 9 summarizes the installed cost data for the different array mounting configurations. As is seen, the integral mounted array, wherein the modules are a structural roof member, has the lowest cost. Next lowest is the direct mounted array, wherein the module is placed on top of the roof over the waterproof membrane. The ground-mounted rack is most expensive. As can be seen from the table, cost drivers include the panel/module support frame, mounting gaskets, and the installation of the panel/module. Cost reductions are possible through design of integrated modules and arrays. This effort should begin soon to meet the goals of the Photovoltaics Program.

Table 9. Array Mounting Configuration Installation Cost Summary
for 32 by 96 Inch Panel/Modules

COST COMPONENT	ARRAY INSTALLATION COSTS, 1975 \$/m ²				
	INTEGRAL	DIRECT	STANDOFF	RACK	
				ROOF	GROUND
• Wiring ¹	5.90	5.90	6.40	6.40	6.40
• Panel/Module Support Frame	5.80	10.40	14.20	12.80	12.80
• Panel/Module Installation	19.60	19.20	6.70	6.70	6.70
• Mounting Gaskets	9.40	4.80	8.90	-	-
• Sealant	-	0.70	-	3.20	3.20
• Roof Bracing	1.70	-	-	-	-
• Flashing	-	-	5.40	5.30	-
• Rack Structure ²	-	-	-	11.90	12.30
• Fence ³	-	-	-	-	17.00
Installation Cost	42.40	41.00	41.60	46.30	58.40
Roofing Credit ⁴	17.10	10.40	-	-	-
Total Installed Cost 1975 \$/m ²	25.30	30.60	41.60	46.30	58.40
(1980 \$/m ²)	(35.50)	(42.90)	(58.30)	(64.90)	(81.80)

NOTES:

1. 220 Vdc
2. Wood structure. Includes concrete footings for ground-mounted rack arrays.
3. Needed for safety.
4. Credit for normal roofing materials displaced by the photovoltaic array. For integral mounting, it includes the cost of ½ inch plywood, 15# felt paper, and 325# asphalt shingles. For direct mounting, it is the cost of 325# asphalt shingles.

Section 5

CONCLUSIONS

Conclusions of this study are that:

1. In order to penetrate the housing industry, residential photovoltaic modules and arrays must comply with building codes and their referenced standards.
2. A review of current building codes and their referenced standards found that: a) there were no perceived major obstacles to the development and eventual implementation of photovoltaic modules and arrays into the housing industry, b) residential photovoltaic modules and arrays will have to comply with the National Electrical Code (NEC), and c) there are no applicable code categories for photovoltaic modules and arrays. With no code category for photovoltaic modules and arrays, existing categories would be used by local building code officials resulting in possible restriction or rejection
3. Product approval of photovoltaic modules and arrays by a nationally recognized testing laboratory, indicating compliance with all industry-accepted standards, will accelerate acceptance by local building code officials.
4. Code approval, acceptance by building code groups of photovoltaic modules and arrays which have product approval, will be necessary for widespread application of photovoltaic power systems.
5. For ease of installation, modules should be 32 by 96 inches and weigh 50 to 120 pounds. Significantly higher costs results when using smaller modules to achieve panel sizes of 32 by 96 inches.
6. Integral mounting, wherein modules are a structural roof member, had the lowest installed cost - $\$28.30/\text{m}^2$ (1975\$) - and were aesthetically acceptable. Direct mounting, wherein the modules are attached to the roof over the waterproof membrane, had higher costs than integral mounting and were aesthetically acceptable. Standoff mounting, where the modules are not touching the roof, had higher costs but questionable aesthetics. Rack mounting is not recommended for other than flat-top roofs because of high costs, high point loading, and aesthetic problems.

7. In general, grounding is required, particularly when metal module support frames are used. Module and array designs that can demonstrate effective electrical isolation, as verified by a nationally recognized testing laboratory, may be granted an exemption.
8. Array wiring costs increase greatly as module size is reduced but do not vary significantly among the four array mounting configurations. Wiring costs are inversely proportional to branch circuit voltage level, the optimum (minimum) being between 100 Vdc and 300 Vdc. Electrical terminations are the principal cost drivers for array branch circuit wiring, although a modular quick connect wiring system can be significantly less expensive than junction box wiring systems particularly when the branch circuit wiring is exposed to weather. Copper wire, No. 14 AWG, should be used. In dry locations, non-metallic sheathed (Type NM) or armored (Type BX) cable should be used. In wet locations, underground feeder and branch circuit (Type UF) cable should be used. Although wire sizes smaller in diameter than No. 14 AWG could be used, the greater volume production of No. 14 AWG gives it significant economic advantage.
9. Integral and direct mounted modules and arrays must be qualified to UL 790, "Tests for Fire Resistance of Roof Covering Materials," Class A, B, or C. Further investigation is needed to determine which fire class is appropriate. Standoff and rack-mounted modules and arrays, if used, must have their plastic encapsulants qualified to ASTM D 635, "Flammability of Rigid Plastics Over 0.05 Inches in Thickness," and, if qualified, would be limited in roof area to between 20 and 30 percent of floor area.
10. A 50 psf design load will be acceptable for over 90 percent of the U. S. In areas with snow loads greater than 40 psf - portions of the Northeast, the Rocky Mountains, and Northwest - a higher design load or different installation may be necessary.
11. Aesthetically, the module should approximate the matte-like (non-glare) texture of the roof; be rectangular (aspect ratio of approximately 2 to 1); and be a dark earth tone similar to surrounding

roof material. The array should lie in and be a continuation of the roof plane and its texture. The array should not create a dominant (easily identified) pattern. The array should be as small as possible to avoid being a dominant monolithic feature, preferably 800 ft² (74 m²) or less.

12. Shipping and handling is one of the worse environments a module will have to face. Until an industry standard is developed, MIL-STD-810C, Method 516.2, Procedure I (shipping test) and Procedure II (transit drop test) should be used to qualify packaged modules for shipping. In the field, if flexural rigidity is required during handling, the module manufacturer should provide temporary stiffeners.
13. The module and array should be considered as roofing material, implying a maintenance-free design and a design life of 20 years. The module should have as high as efficiency as possible -- 13.5 percent at NOCT or greater.

Section 6

RECOMMENDATIONS

Recommendations of this study are that:

1. Studies similar to this one should be conducted to determine the design requirements for the rest of the residential photovoltaic power system. The results of both studies should be checked to ensure that no distortion resulted from the two separate studies.
2. A flexible performance criteria document for residential photovoltaic systems should be developed as a first step to provide guidance to the photovoltaic industry and local building code officials (Appendix 19 contains a draft residential array performance criteria). Second, forming photovoltaic subcommittees in model codes groups is recommended after the performance criteria document is developed. It is not recommended to first develop photovoltaic model codes because such efforts would take too long and they could stifle innovation.
3. Because of its importance and long lead time, the National Electrical Code (NEC) should be contacted and a photovoltaic subcommittee formed by the end of 1979 so that codes, based on the performance criteria document, can be developed for publication in the 1984 Edition of the NEC.
4. Representatives of the photovoltaic industry should work with consensus standards groups to develop relevant industry standards.
5. A workshop should be held discussing residential photovoltaic systems and their implications on the housing industry with representatives from the photovoltaic industry, supporting industries, model code groups, testing laboratories, building code officials, and government officials. This workshop would familiarize the housing industry with photovoltaics and the photovoltaics industry with the housing industry.
6. Design of integrated modules and arrays should be initiated soon and be based on the results of this report. Concurrent with array design, component development, such as the modular quick-connect terminations, should be initiated soon. Field testing of prototype

modules and their resultant arrays should be performed to validate installation techniques and determine long-term performance.

7. Existing and prototype modules should be tested under UL 790, "Tests for Fire Resistance of Roof Covering Materials," and ASTM D 635, "Flammability of Rigid Plastics over 0.05 Inches in Thickness" to establish fire resistance of current module designs and encapsulation materials.
8. Early market entry scenarios should be developed. The special steps required for the first penetration of a new product into the housing industry were not part of this study but is needed.
9. Module manufacturers should obtain and keep current editions of the building codes and referenced standards. A listing, including costs, is provided in Appendix 9.

Section 7

NEW TECHNOLOGY

No reportable items of new technology have been identified during the conduct of this study.